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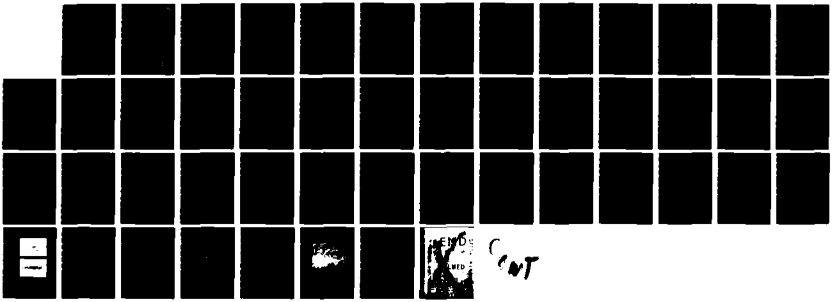

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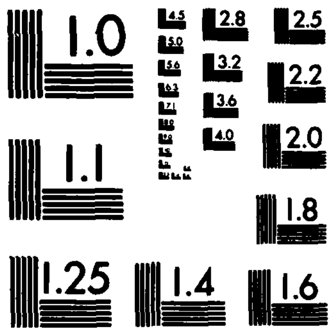

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CHEMICAL REACTIONS in TURBULENT MIXING FLOWS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work under this contract has proceeded along three main lines, (i) an experimental program covering low heat release combustion of hydrogen and fluorine, and chemically reacting turbulent shear layers and jets in water, (ii) a theoretical model development program whose aim is to provide alternatives to gradient diffusion transport models, and (iii) a diagnostics development parallel program to advance the state-of-the-art in experimental techniques, as dictated by our main experimental effort. Substantial

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progress has been made in all three areas. Notably, in the experimental program, we have completed a first set of measurements in our $H_2 + F_2$ combustion facility, as well as laser induced fluorescence measurements of chemically reacting jets and shear layers in water. These experiments prove conclusively that gradient transport models are inappropriate in describing these flows. In the theoretical area, we have shown good agreement between a simple mixing model, developed under this contract sponsorship, and our measurements. In the diagnositcs area, important advances have been made in laser Doppler velocimeter, high speed thermometry, laser induced fluorescence and others.

Executive summary

Work under this contract has proceeded along three main lines, (i) an experimental program covering low heat release combustion of hydrogen and fluorine, and chemically reacting turbulent shear layers and jets in water, (ii) a theoretical model development program whose aim is to provide alternatives to gradient diffusion transport models, and (iii) a diagnostics development parallel program to advance the state-of-the-art in experimental techniques, as dictated by our main experimental effort. Substantial progress has been made in all three areas. Notably, in the experimental program, we have completed a first set of measurements in our H_2 + F_2 combustion facility, as well as laser induced fluorescence measurements of chemically reacting jets and shear layers in water. These experiments prove conclusively that gradient transport models are inappropriate in describing these flows. In the theoretical area, we have shown good agreement between a simple mixing model, developed under this contract sponsorship, and our measurements. In the diagnostics area, important advances have been made in laser Doppler velocimetry, high speed thermometry, laser induced fluorescence and others.

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LIST of SYMBOLS

c_p	product concentration
C_{01}	high speed stream reactant concentration
d	jet diameter
F_2	fluorine
H_2	hydrogen
HF	hydrogen fluoride
I(y)	instantaneous fluorescence intensity distribution
L-s	flame length measured from virtual origin of turbulent region
$(L-s)_\infty$	flame length at high Reynolds number
LIF	laser induced fluorescence
N_2	nitrogen
P_1	product thickness (defined in figure 4)
PDF,pdf	probability density function
Re	Reynolds number
ΔT	temperature rise
$\overline{\Delta T}$	mean temperature rise
Tflm	adiabatic temperature rise
Tmax	maximum instantaneous observed temperature rise
x	streamwise coordinate
x_0	shear layer virtual streamwise origin
y	cross-stream ccoordinate

List of Symbols

U_1	shear layer high speed velocity
U_2	" " low " "
U_c	$= (U_1+U_2)/2$, shear layer convection velocity

Greek symbols

δ	vorticity thickness
η	$= y/(x-x_0)$
λ	wavelength of light
ξ_ϕ	high speed volume fraction corresponding to complete consumption of reactants as a function of the equivalence ratio ϕ
ϕ, Φ	equivalence ratio

1.0 RESEARCH CURRENTLY UNDER WAY.

1.1 TECHNICAL OBJECTIVE

This is an investigation of the fundamental mechanisms of turbulent mixing, chemical reactions and combustion in free shear flows, including the effects of,

- heat release,
- flow velocity (Reynolds number),
- reactant concentrations (equivalence ratio),
- mass diffusion rates (Schmidt number),
- velocity ratio across the region of shear,
- density ratio of the mixing streams.

The work at present is concentrated in the subsonic flow regime. It should be mentioned, however, that the shear flow combustion facility presently utilized for the low heat release $H_2 + F_2$ combustion experiments has been designed to be modifiable for supersonic flow combustion experiments in the future.

1.2 APPROACH UTILIZED.

The work under this contract can be divided into three inter-related activities,

1. an experimental effort focusing on the exploration and documentation of the various related flow and combustion phenomena,

2. a theoretical effort focusing on developing analytical and, eventually, computational models,

3. a diagnostics development effort to provide the experimental tools beyond presently available state-of-the-art as dictated by the on-going or anticipated needs of the experimental program.

It should be emphasized that these parts are to be viewed as a single effort. The various experimental, theoretical and diagnostics activities closely support and complement each other, and are undertaken only to the extent that they serve an identifiable need within the overall framework of our goal: to understand the fundamental phenomena and mechanisms that govern turbulent mixing, chemical reactions and combustion.

2.0 PROGRESS DURING THE PAST 12 MONTHS.

2.1 EXPERIMENTAL EFFORT.

The experimental activities during the last 12 months concentrated on the following major areas.

2.1.1 Low heat release $H_2 + F_2$ combustion experiments.

Work this last year concentrated on a low heat release investigation using combustion of hydrogen and fluorine in a turbulent, two-dimensional mixing layer at low reactant concentrations (low heat release) for a wide range of reactant equivalence (concentration) ratios. These highly exothermic chemicals react spontaneously to form hydrogen fluoride, obviating flame holders and igniters. Our results offer new insight into the combustion process and provide a reliable data base with which computational and/or analytic models can be compared. Sample experimental results are depicted in figures 1 through 4.

Figure 1 shows the time/space-resolved temperature in a turbulent combustion shear layer with a 1% F_2 molar concentration carried in a N_2 diluent on the high speed stream, and a 4% H_2 concentration carried in a N_2 diluent on the low speed stream, measured at eight locations across the shear layer. The velocities across the shear layer were $U_1 = 22$ m/s

and U_2 = 8.8 m/s respectively. These time traces can be understood in terms of the large scale structures in the flow, and yield the mean temperature (or chemical product) profiles when integrated as a function of time. See figure 2. Note that the adiabatic flame temperature is not achieved, in the mean, at any location. Note that the adiabatic flame temperature, neglecting Lewis number effects, will be observed on the interface of strained flamelets throughout the flow, but cannot be resolved by presently available instrumentation owing to resolution limitations and conduction errors. Also shown in figure 2 are the highest and lowest temperature recorded by each probe. It is significant that the layer can be nearly uniformly hot or cold across its whole extent at a time, and that the conventional bell-shaped mean profile arises simply because the outer edges of the mixed region sample the hot products less often than the center.

These results contradict predictions of conventional gradient diffusion models, as do the mean profiles for the range of equivalence ratios investigated. See figure 3.

Note that the mean product (temperature) profile measured for reciprocal pairs of the equivalence ratio (eg. ϕ = 8 & 1/8, 4 & 1/4, 2 & 1/2, etc.) corresponding to a simple exchange of the side of the shear layer (free stream) where the reactants are carried, with no other change in the conditions, lead to significant and systematically different product profiles. This result, which has been confirmed by independent experiments in water (Koochesfahani et al 1983) and is consistent with earlier measurements in our laboratory of non-reacting shear layers (Konrad 1976), is badly at variance with predictions of known analytical or computational turbulence models and is a consequence of the important fact that <u>the shear layer entrains and mixes an excess of high speed fluid</u>. Note also that the shift in the location of the peak mean temperature, over a range of the equivalence ratio of a factor of 64 (1/8 to 8), is relatively small. This argues for a probability density function for the mixed reactants that, except for a change in the scaling of the PDF of the mixed fluid as a function of position in the layer, is nearly uniform from one extreme to the other. This conclusion, which is supported by independent measurements in the past (Konrad 1976), and other experiments under this contract (see section 2.1.2), is also in serious contradiction with known models of this process.

Figure 4 depicts the integrated product thickness across the shear layer, as a function of the free stream concentration (equivalence) ratio. It can be seen that the dependence of the total amount of

product on the equivalence ratio can be separated into two regimes. For small values of the equivalence ratio, the amount of product formed in the layer increases monotonically with equivalence ratio. For values of the equivalence ratio greater than about 6, however, there is very little change in the total product. These two regimes correspond to the consumption of the lean reactant in each case. For low values of ϕ, the entrained fluid from the low speed side is in short supply, and the total amount of product is nearly proportional to the low speed side reactant concentration. As the low speed side concentration is increased, however, a point is reached point where the entrained fluid from the high speed side becomes the limiting quantity and further increase in the concentration of low speed fluid does not produce a commensurate increase in the total product. This can also be illustrated by normalizing the product thickness by the quantity $\phi/(\phi+1)$, which is proportional to the dependence of the adiabatic flame temperature on the equivalence ratio ϕ, for a fixed reactant concentration on the high speed side. The normalized data are depicted in figure 5.

Finally, a significant result is that there is approximately 35% more product formed in a gas than in a liquid, implying that the molecular diffusion coefficient (Schmidt number) plays an important role in turbulent mixing. This conclusion is to be contrasted with the predictions of conventional turbulence models, which prescribe the effective turbulent diffusivity as a function of the <u>flow</u>, as opposed to

the fluid, and are therefore unable to accommodate, let alone predict, this behavior.

These and other results related to this particular effort will be reported at the 1982 AFOSR contractors' meeting, Clearwater Florida (Liepmann et al 1982), at the AIAA 21st Aerospace Sciences Meeting (Mungal, Dimotakis and Broadwell 1983), and as a CALTECH Ph.D. thesis (Mungal 1983), during the current contract period (see reference section).

2.1.2 Chemically reacting shear layers in water.

To investigate some of the Schmidt number effects mentioned in the preceding section, by comparing the results to those in the corresponding gas combustion experiments, and to exploit the power of the Laser Induced Fluorescence (LIF) diagnostics, developed previously under this contract, we have also undertaken a parallel investigation of some of these effects in a reacting shear layer (acid, base reaction) in water.

A first set of experiments was performed, designed to explore the implications of the asymmetric entrainment into the two-dimensional turbulent shear layer. Using an acid base reaction and a pH sensitive fluorescent dye, it was possible to monitor the chemical environment, on a molecular scale, of the mixing fluids brought together in the shear

layer. Using selected values of the equivalence ratio it was possible to arrange for a difference in the overall chemical production, in this reversible chemical reaction, of the order of two orders of magnitude by exchanging the side that carries the lean reactant. Sample comparison data from these experiments are depicted in figure 6. Again, it should be emphasized that the conventional gradient diffusion models that we are aware of cannot predict or account for this striking effect. Preliminary results of this work will be reported in the 1982 AFOSR contractors' meeting and in the AIAA 21st Aerospace Sciences Meeting, 10-13 January 1983 (Koochesfahani, Dimotakis and Broadwell 1983).

Experiments currently under way in this effort, using a combination of Laser Induced Fluorescence (LIF) techniques and high speed, real time digital image acquisition techniques (see sections 2.3.2 & 2.3.3) on the chemically reacting shear layer in water, are yielding direct measurements of the probability density function (pdf). This very exciting development will allow direct verification of some of our ideas. Preliminary data from this effort will be presented in the 1982 AFOSR contractors' meeting in Clearwater, Florida (see also Liepmann et al 1982). Sample pdf data, constructed from a direct sorting of raw LIF measurements, are depicted in figure 7.

2.1.3 Chemically reacting jets in water.

Work in this area, during the last 12 months, has concentrated in the study of Reynolds number effects on the entrainment and mixing of round turbulent jets. A variety of conflicting documentation exists in the literature concerned with this issue, that placed the value for a minimum Reynolds number required for the asymptotic behavior anywhere from 4,000 to 40,000.

Careful measurements performed during the last 12 months, using LIF techniques and carefully controlled flow conditions suggest that, in fact, the minimum value of the Reynolds number is probably close to 3,000. The discrepancy between our result (which we have no reason to doubt) and previous experiments conducted elsewhere is probably due to the difficulties associated with such measurements if they are made with less definitive diagnostics.

A second result of this work, of quite some interest however, was the discovery of the systematic way the asymptotic value of the entrainment and mixing is attained as a function of the equivallence ratio. For small values of the equivalence ratio ϕ, the flame length - defined here as the distance from the origin to the farthest streamwise station where unreacted jet fluid is observed - is found to <u>decrease</u> with increasing Reynolds number towards its asymptotic value, whereas for larger values ($\phi > 10$) the flame length <u>increases</u> towards its asymptotic value. This rather surprising behavior provides us with

valuable clues regarding the dependence of the entrainment and mixing processes on the distance x/d from the jet origin. Sample data of the flame length as a function of the equivalence ratio are depicted in figures 8 and 9.

An earlier phase of the investigation of the behavior of turbulent jets, using laser induced fluorescence and particle streak techniques, was presented earlier this year (Dimotakis, Miake-Lye and Papantoniou 1982) as a GALCIT report FM82-01, to be published in the Physics of Fluids, November 1983. Aspects of that earlier phase were also supported by The Boeing Airplane Company, with a particular interest in jet noise.

A first phase of the work on chemically reacting jets will be presented at the AIAA 21st Aerospace Meeting (Dimotakis, Broadwell and Howard 1983). A more extensive GALCIT report of progress to date will be completed during the current contract period. Aspects of this particular effort are also supported by the EPA.

2.2 THEORETICAL EFFORT

Our primary effort in this area these last 12 months has concentrated on correlating the predictions of the Broadwell, Breidenthal mixing model (Broadwell, Breidenthal 1981), with experimental results, primarily the HF combustion data (see section 2.1.1), and preparing the material for publication in the Journal of Fluid Mechanics.

Additional effort has been expended in order to understand the the unequal entrainment of the two free stream fluids into the turbulent mixing layer, and its dependence on velocity and density ratio. We are also attempting to define a unified model of the mixing process, that would treat the transition from the pure flame sheet contribution to the homogeneously mixed fluid contribution to the overall product in a unified way. These are preliminary exploratory efforts, at this point however, and no reportable results are available as yet.

2.3 DIAGNOSTICS DEVELOPMENT

An important part of the present work is a parallel effort to develop diagnostic tools that advance the state-of-the-art in areas that our primary experimental effort dictates the development. It should be emphasized that this part of the effort is only justified, in our minds, as the supplier of the diagnostic technology required by our experiments. No diagnostic development effort is undertaken, unless a clear need for the particular technique can be defined, and no acceptable alternatives are available.

Progress in this area in the last 12 months has concentrated in the following areas.

2.3.1 Multi-channel Laser Doppler Velocimetry.

A four channel laser Doppler velocimeter system was completed during the last 12 months. The system has presently been configured to perform, what we believe to be, the first time and space resolved spanwise vorticity measurements in a two-dimensional, turbulent mixing layer. Four pairs of beams are focused and cross on the vertices of a small square, 1 to 4 mm on edge, and aligned to measure the appropriate velocity components required to compute the spanwise component of the curl (and therefore the vorticity) at the desired point. The system is capable of very high accuracies which permit the differencing of the four separate measurements, as required by the computation of the curl.

Preliminary measurements to date in the shear layer (velocity ratio of 2.2:1) indicate that the instantaneous vorticity can be negative, possibly reflecting the longevity of the wake component from the splitter plate that separates the two streams at the shear layer origin. This important discovery may provide some guidance in designing computational schemes based on point vortex methods; no such possibility has been built in any such codes that we are aware of.

These preliminary results will be reported at the 35th annual meeting of the Division of Fluid Dynamics of the American Physical Society (Lang and Dimotakis 1982). The vorticity measurements are supported, in part, by the National Science Foundation.

2.3.2 Laser induced fluorescence techniques.

Laser Induced Fluorescence (LIF), developed under this contract a few years ago, has proven to be one of the most powerful probes in our research of turbulent mixing and reacting flows. Most of the data using LIF techniques to date, however, have been recorded on photographic film. Consequently, quantitative measurements had been difficult and only estimates of various quantities of interest have been warranted. Whereas it is certainly possible to calibrate photographic film as a quantitative recording medium, problems of finite depth resolution and reproducibility of a difficult calibration procedure had led us from the very beginning to consider alternative recording techniques which by-pass film altogether. We have recently succeeded in performing such measurements using a multi-element (512) photosensitive diode array, built by RETICON, and interfaced by us to a PDP-11 computer based data acquisition system (see section 2.3.3 below). Imaging the fluorescence emitted from a collimated laser beam crossing a turbulent mixing layer, and recording the resulting fluorescence intensity as a function of y, the transverse coordinate, and time, we were able to acquire quantitative species concentration measurements at 512 points across the layer, as a function of time for 384 successive scans for a total of 196,608 measurements of point concentrations, recorded with an accuracy of roughly 2-3% each in 300 msec of real time and a spatial resolution of 100 μm in the transverse dimension of the flow.

A schematic of the optics and recording apparatus is indicated in figure 10. Sample data for a Reynolds number of the order of 1,000 are depicted in figure 11. These data will also be presented at the 1982 AFOSR contractors' meeting in Clearwater Florida. The probability density functions in figure 7 were computed from similar data, recorded at a higher Reynolds number. It is instructive to reflect on the difference of the quality of information afforded by figure 11, as compared to the conventional statistical data, at its best, represented by figure 7.

This revolutionary development will permit a variety of measurements to be performed that would have been impractical to consider in the past. The kind of data depicted in figure 11, and present day image processing technology that is increasingly being made available off-the-shelf we believe will permit substantial advances to be made in this area.

2.3.3 High speed digital image recording techniques.

The kind of data that are generated by the solid state image arrays described in the preceding section, as well as the anticipated data rates from the next generation of high speed thermometers (see section 2.3.5) have dictated a separate effort to upgrade existing data acquisition technology.

The first problem to be solved is converting analog data to digital form at rates that are high, by conventional present day standards. These rates are dictated by the clock frequencies of Charged Coupled Device (CCD) image arrays, which can range from a few tens of Kilohertz to a few Megahertz. In addition, our need to measure continuous high frequency analog processes, at several points in the flow at a time, such as result for example from an array of short time response thermometers. To this end, we have completed a single channel data acquisition system, which is capable of conversion speeds of up to 10^7 samples per second at eight bit accuracy. The resulting digital data stream has been interfaced to a general purpose, synchronous data acquisition and control bus (christened D-Bus) capable of 6 MWord/sec (or 12 MBytes/sec).

The first bottle-neck occurs in accessing commercially available computer bus systems that are sufficiently portable and sufficiently inexpensive that they can be dedicated to an experiment when it is running. We have decided to defer the ultimate solution to the latter

problem and wait for commercially available small computers to become fast enough. In the meanwhile, we have designed and fabricated a Direct Memory Access (DMA) interface between our D-Bus and DEC's Q-Bus, which are able to drive in this fashion, provided no other competing activity is sharing the bus, at 1.2 MBytes/sec. The data appearing in figure 11 were acquired using this system at a rate of 500,000 pixels per second, each pixel converted to eight bits (0.5 MBytes/sec).

At present, if we wish to sustain this rate, we can only do so by silencing all other devices on the computer bus. This limits the total data acquired to approximately 200,000 bytes per run. This was also the same upper limit that constrained the data recorded in the combusting H_2, F_2 facility experiments. We are considering two alternatives to removing this shortcoming. One would improve the combined interfacing of the D-Bus and the system's high speed disk, so as to share the bus cycles more efficiently, permitting the disk to be used at nearly the same speed as memory, thereby increasing the effectively available memory to the high speed data acquisition tasks. The second would improve the memory management of the system to permit considerably more memory to be supported by the computer. This could increase the amount of data that can be recorded by as much as an order of magnitude, with no loss in the instantaneous data rate. The decision between these two alternatives, or a possible combination of the two, will be taken during the next contract period. In addition, a high speed analog multi-plexing system, to be used upstream of the high speed analog to

digital converter system, is also under consideration.

2.3.4 Ultrasonic fluid diagnostic techniques.

A system capable of illuminating ("insonifying" for the purists) a flow field with ultrasonic waves and measuring the amplitude and phase distribution of the transmitted wave as a function of time was constructed. A large area transmitter and a linear receiving array were used as transducers. Parallel signal processing and interleaved data conversion and acquisition permit a maximum frame rate of 10 kHz.

The feasibility of measuring velocity disturbances with ultrasound was demonstrated by transmitting sound through a vortex, which was generated in a circular duct by an airfoil swirl generator. Assuming a simple model for the velocity profile about the vortex core, the parameters describing the azimuthal velocity field were determined using this non-intrusive technique. This development and the resulting measurements have been documented in a Ph. D. thesis completed during the last 12 months (Trebitz 1982).

We are presently exploring the possibility of using a variant of this method in the combustion facility, in the hope that it will allow measurements to be taken at high temperatures at which our temperature probes (see section 2.3.5) may possibly not be used as reliable

diagnostic tools, due to radiative complications.

2.3.5 High speed thermometry.

After a careful examination of the potential of a variety of diagnostic techniques for use in the HF combustion facility (see experimental effort section 2.1.1), we decided that (cold) wire thermometry would be the best diagnostic in terms of scientific return versus development investment. While several alternative techniques are presently under consideration, we still believe this method to be a reliable means of obtaining information in these experiments.

To this end, we have developed the fabrication technology to produce very fine wires, 2.5 micrometer diameter and of the order of 1.5 mm in span, whose sensitivity at a signal-to-noise ratio of unity, at the A/D converter input port, is of the order of 0.1 K. These wires are supported by appropriate mounts designed to withstand the harsh chemical and thermal environment to be found in the hydrogen-fluorine combustion facility. We expect them to perform satisfactorily up to temperatures of the order of 1,000 K. The (uncompensated) time response of these wires, at velocities of the order of 20 m/sec, is approximately 350 micro seconds. This time corresponds to the exponential decay traces, returning the wire temperature to the ambient temperature at the trailing edges of the hot structures, more clearly visible in figure 1

at the measuring stations at the edges of the burning shear layer.

We have examined the possibility of boosting the effective frequency response of these probes using digital compensation techniques. Unfortunately, however, even though the wires can be modeled as a first order system which could in principle be inverted to yield the temperature the wire is exposed to, the time constant of this system is not in fact a constant but a sensitive function of the instantaneous velocity. Consequently, improvement of the effective frequency response, without any independent knowledge of the instantaneous velocity, is not justified, in our opinion, by such means at present.

The needs, however, of the experimental program dictate improving the time response even further, particularly as we investigate Reynolds number effects by taking the facility to higher velocities. To this end, and in the absence of any forseeable solution to the digital compensation problem, we have decided to develop wires of even smaller diameter (and therefore heat capacity), which would result in an improvement of our time response by approximately one order of magnitude. We shall be reporting on our progress in this area in our next Scientific Report.

2.3.6 Combustion facility schlieren system.

A schlieren system has recently been installed for flow measurements and visualization of the combusting regions in the H_2, F_2 Reacting Shear Flow Laboratory. The optical system illuminates a 10 inch aperture that can be positioned anywhere in our test section. A folded optical configuration was designed to conform to available space constraints and also so as to be easily moveable, allowing access to all sections of the flow facility. The system layout is shown in figure 12.

This optical system is presently operational. Preliminary tests have resulted in acceptable image quality and sensitivity. Initial flow visualization runs have been made with a spark source synchronized to a motorized 35 mm camera. Sample data will be shown at the AFOSR contractors' meeting in Clearwater Florida.

A planned improvement of this diagnostic tool, to be installed in the 1983-84 contract period, will replace the low repetition rate spark source with a continuous lamp source of adequate power to permit motion picture data of the combustion process to be recorded. The possibility of synchronizing this process with the digitally acquired data from the high speed thermometers in the flow is being investigated.

3.0 TECHNOLOGICAL SIGNIFICANCE.

The results of the present research effort are applicable directly to a variety of technological problems that are awaiting progress in understanding in the fields of combustion and chemical reactions in a turbulent mixing environment.

3.1 SIGNIFICANCE to the AIR FORCE.

Many of these results have or will have a significant impact on the Air Force Technology program. More specifically, an increased understanding of turbulent mixing and combustion is needed in a wide variety of technical fields. Some of these include,

a. CHEMICAL LASERS. To a very large degree, the chemical laser is limited in performance by the mixing efficiency and resulting reaction rate between the two streams. An increased understanding of these mechanisms and possible methods of control and/or enhancement of the reaction rate would have an immediate impact on this program.

b. ENGINE and POWER PLANT COMBUSTION. The results of the current research effort can influence the way combustors of all kinds are designed, be they jet engines, power plants, or internal combustion engines. An improved understanding of the turbulent

mixing and combustion processes can potentially reduce the pollution and emissions as well as improve the efficiency of such devices with accompanying reductions in fuel consumption. The importance of such a possibility for the Air Force and the nation as a whole need not be emphasized.

c. JET ENGINE and ROCKET PLUME INFRA-RED EMISSION. The one most important parameter in determining the infra-red emission from a combusting exhaust is temperature. Our current understanding of the exhaust plume mixing and reaction allow us only empirical means of predicting temperatures at present. This lack of understanding is a major hurdle in controlling exhaust infra-red emissions.

d. SUPERSONIC COMBUSTION. We have designed the present high heat release combustion apparatus in a way that would permit modular modifications to achieve supersonic flow and combustion. This capability is difficult to reproduce elsewhere, especially considering the strict specifications we are imposing on the degree of flow quality and document bility . We expect that this program will provide valuable baseline data for supersonic combustion.

3.2 INTEREST IN, and APPLICATIONS of our RESULTS ELSEWHERE.

Our research, both presently and for the last few years under this contract, has been, and is being used in a variety of governmental and industrial laboratories, conducting work on behalf of the Air Force. Notably by,

a. Air Force Weapons Laboratory

b. Army Research Office

c. Several Aerospace companies, including,

TRW

Rockwell

Tetra Corp.

d. Several government laboratories, including,

Los Alamos

Sandia

JPL

e. Aeronautical Research Associates, Princeton.

In addition, of course, these results are influencing in a direct way, through our interaction with the academic community, the research in a large number of university laboratories. We are doing our best to disseminate this information as soon as possible. The references in section 5, represent a list of our recent efforts along those lines.

4.0 CONCLUSIONS.

Our recent experimental and theoretical efforts prove conclusively that the concept of gradient diffusion, used by almost all computational models of turbulent mixing today, is inappropriate as a description of turbulent transport in turbulent shear flows. The implications of this realization are very serious, as the codes presently in use by and on behalf of the Air Force rely on modeling turbulent tranport as a gradient diffusion process.

Based on our experimental results, and our continuing research in this area, we expect to be able to offer credible alternatives to gradient diffusion concepts in the near future. Preliminary theoretical efforts along these lines are very promising.

A parallel effort to develop diagnostic methods dictated by our experimental research program has yielded important new advances in high speed thermometry, laser induced fluorescence, laser Doppler velocimetry, digital image recording techniques and others.

5.0 REFERENCES.

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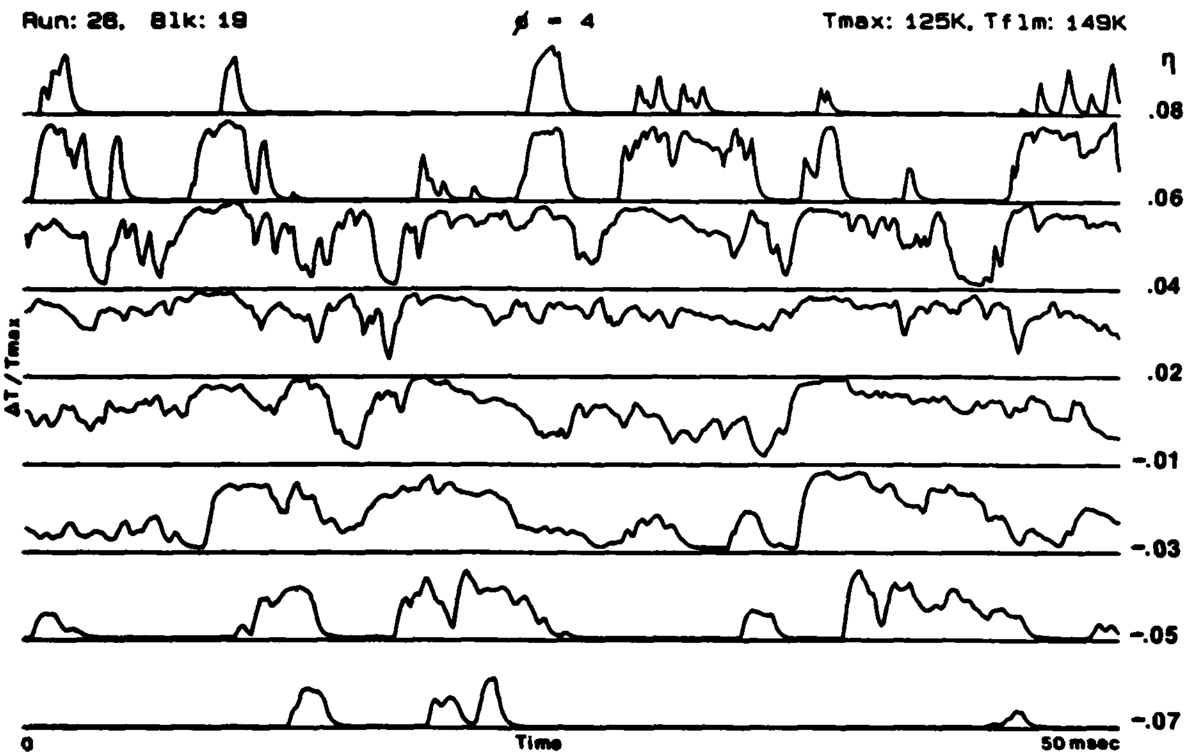


Fig. 1. Simultaneous temperature traces from a $\phi = 4$ run for different values of the normalized transverse coordinate $\eta = y/(x-x_0)$. Note nearly uniform temperatures in the interior of large regions of the flow, extending across the whole shear layer.

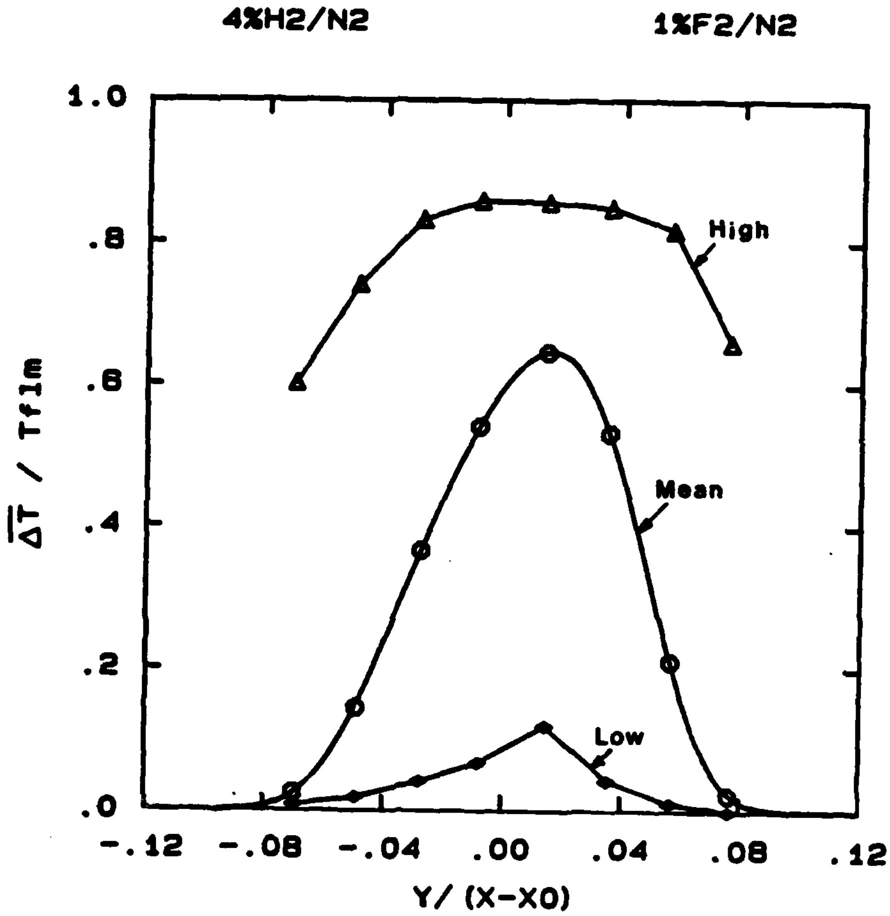


Fig. 2. Mean temperature profile, highest and lowest temperatures observed for the conditions of figure 1.

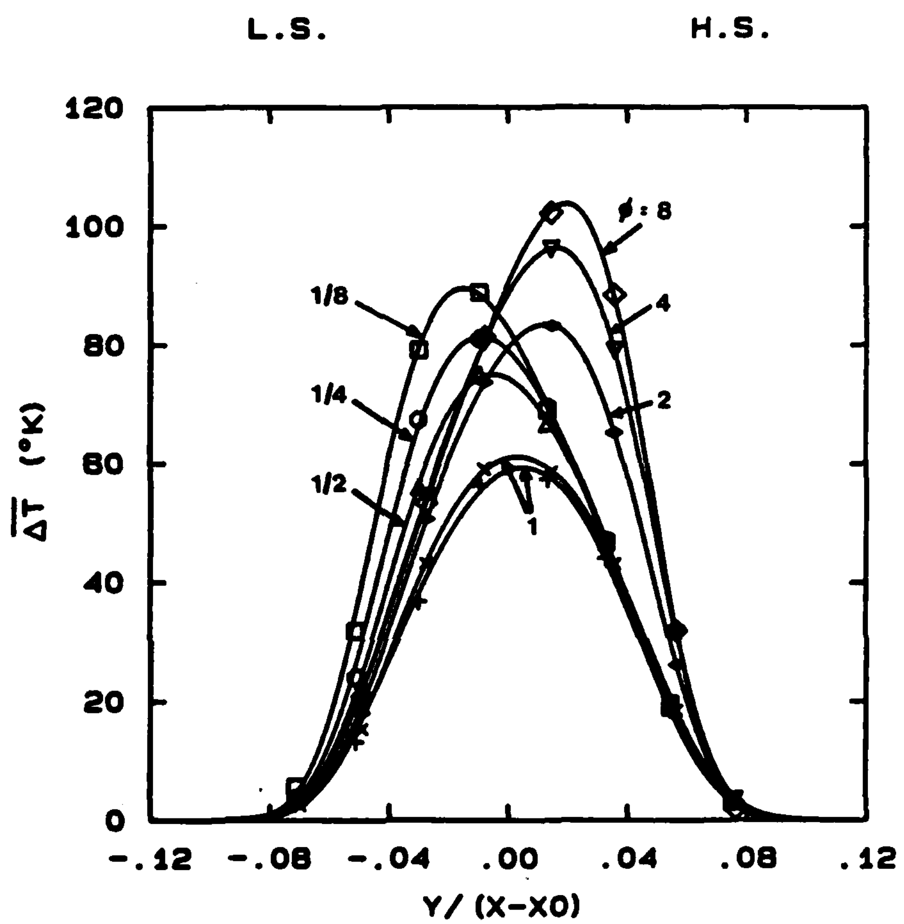


Fig. 3. Mє ⁊ temperature rise profiles, as a function of free stream equivalence ratio.

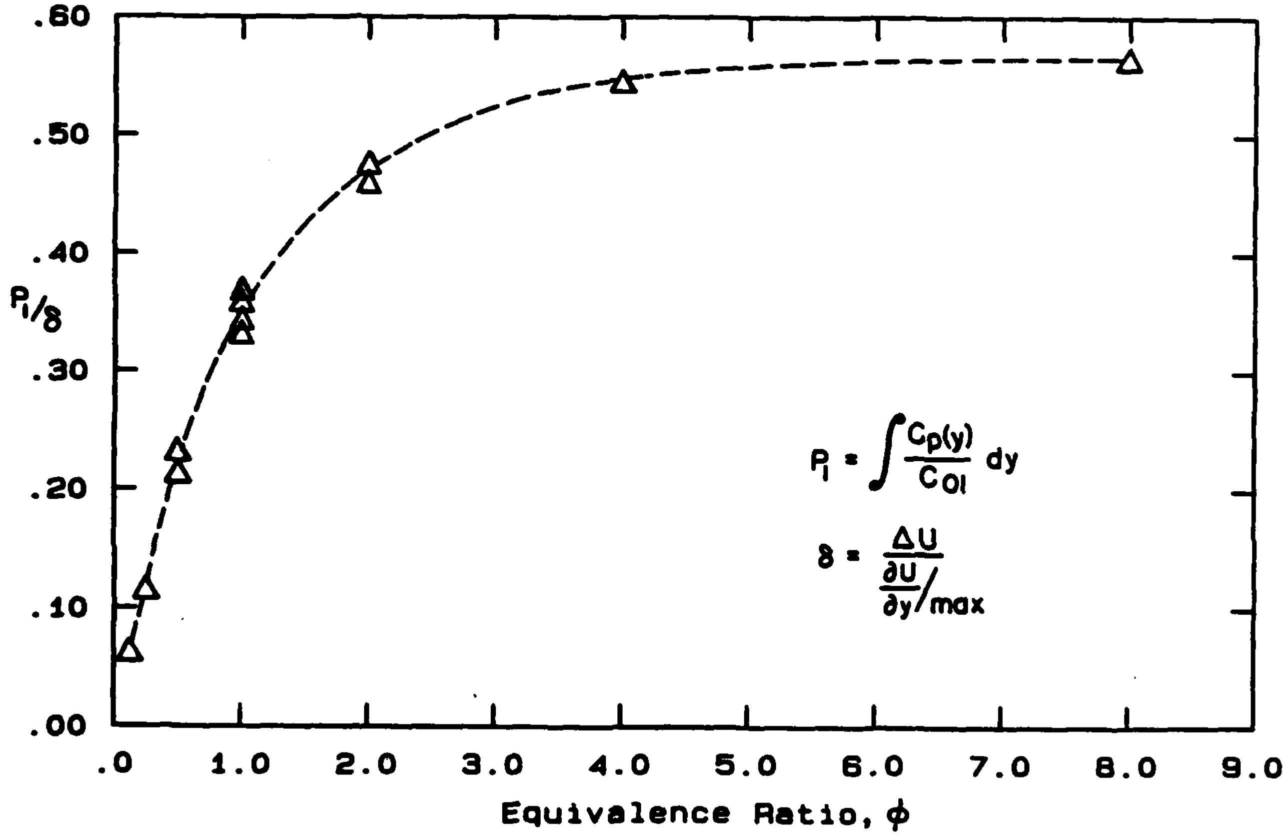


Fig. 4. Normalized product thickness as a function of equivalence ratio.

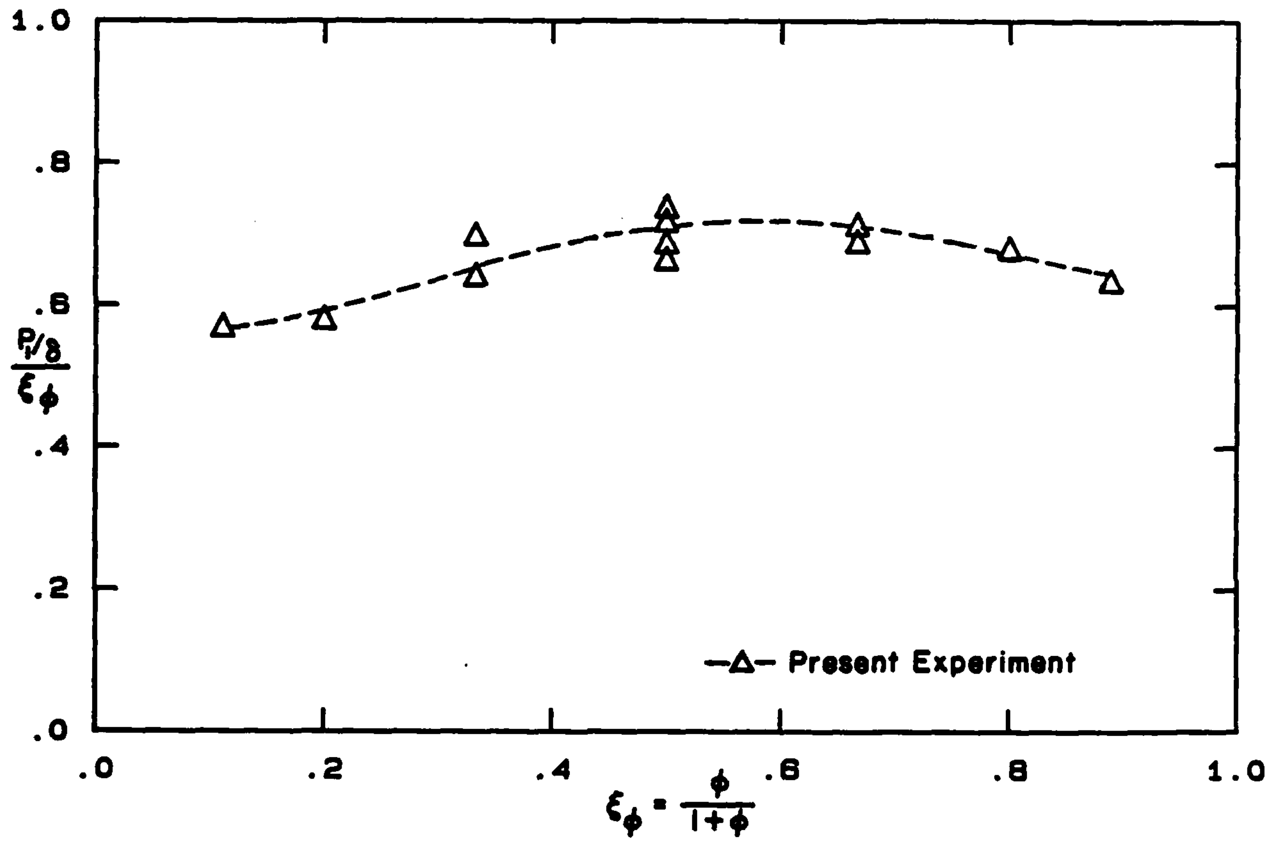


Fig. 5. Normalized product thickness as a function of $\xi_\phi = \phi/(1+\phi)$.

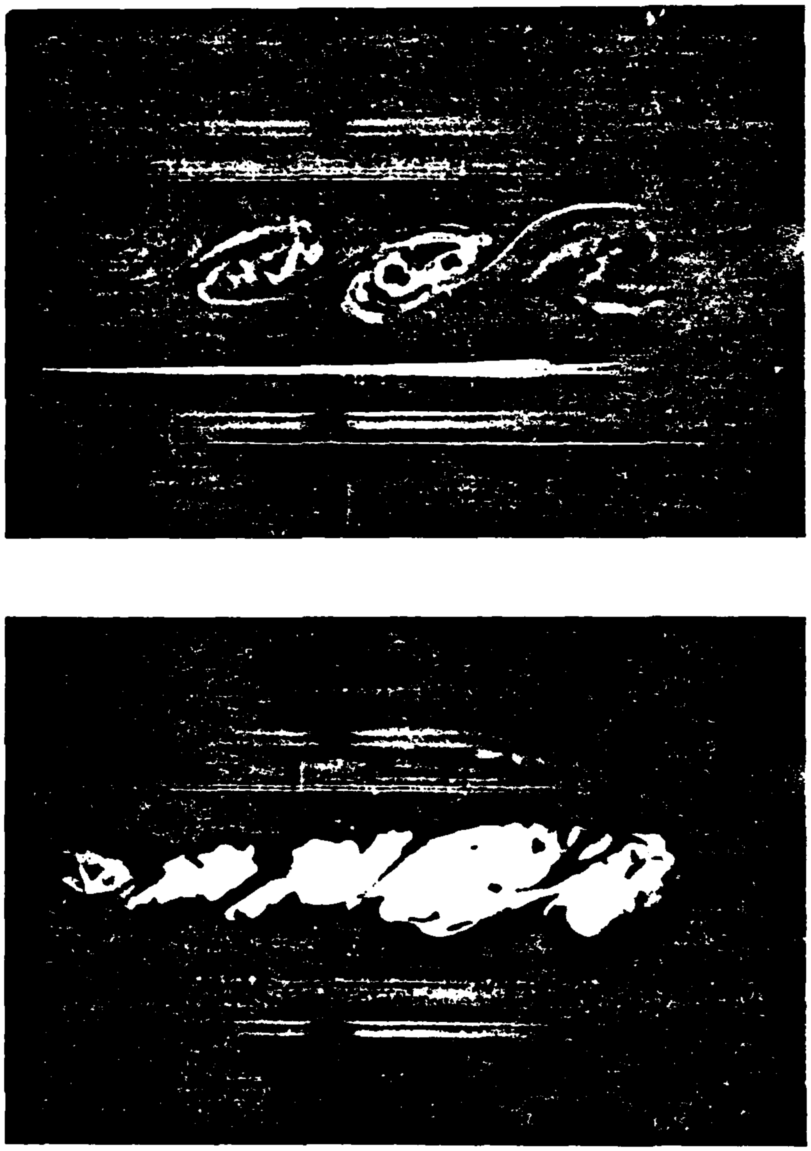


Fig. 6. Reversible chemical reaction in water. Product concentration comparison ($\phi = 1.8$). Identical conditions except for exchanging the chemicals on the high and low speed side of the shear layer.

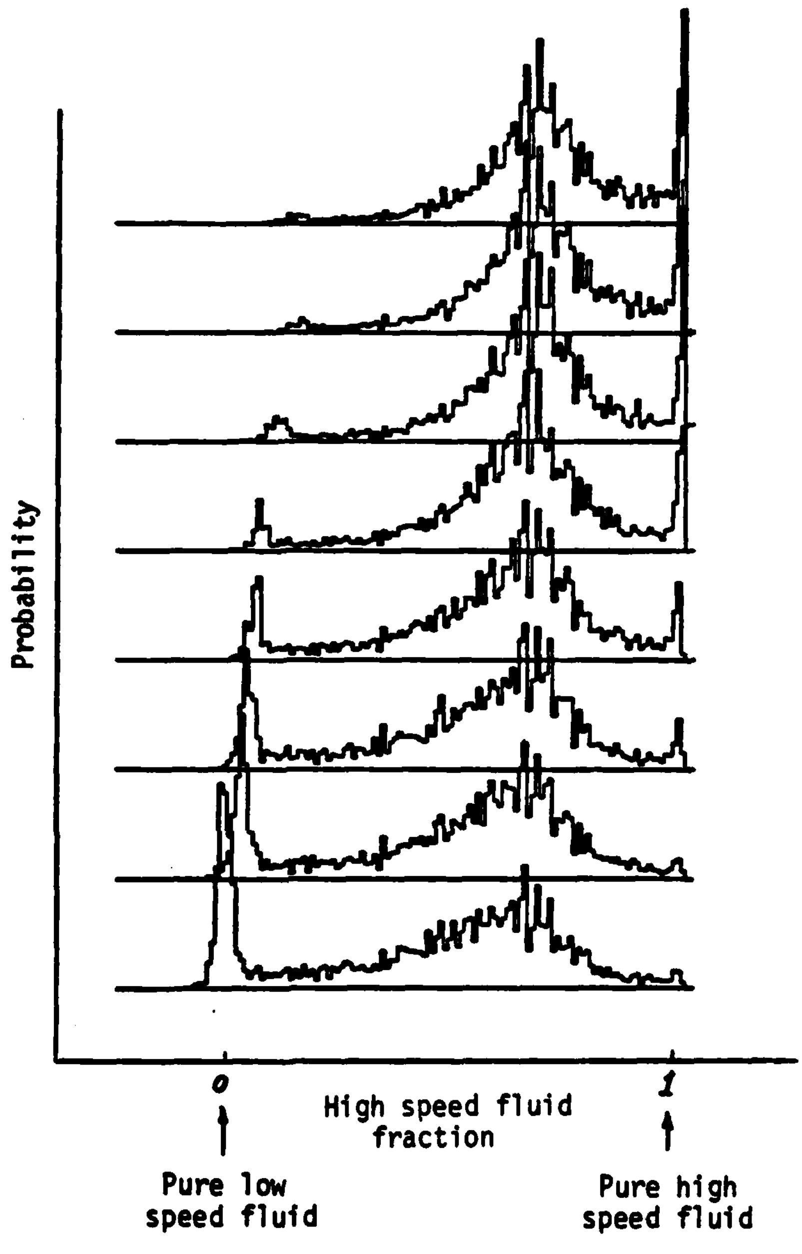


Fig. 7. Preliminary PDF data recorded across the width of a mixing layer (Re = 8,200, U_1/U_2 = 2.65). Note uniform composition of mixed fluid across shear layer with an excess of high speed fluid.

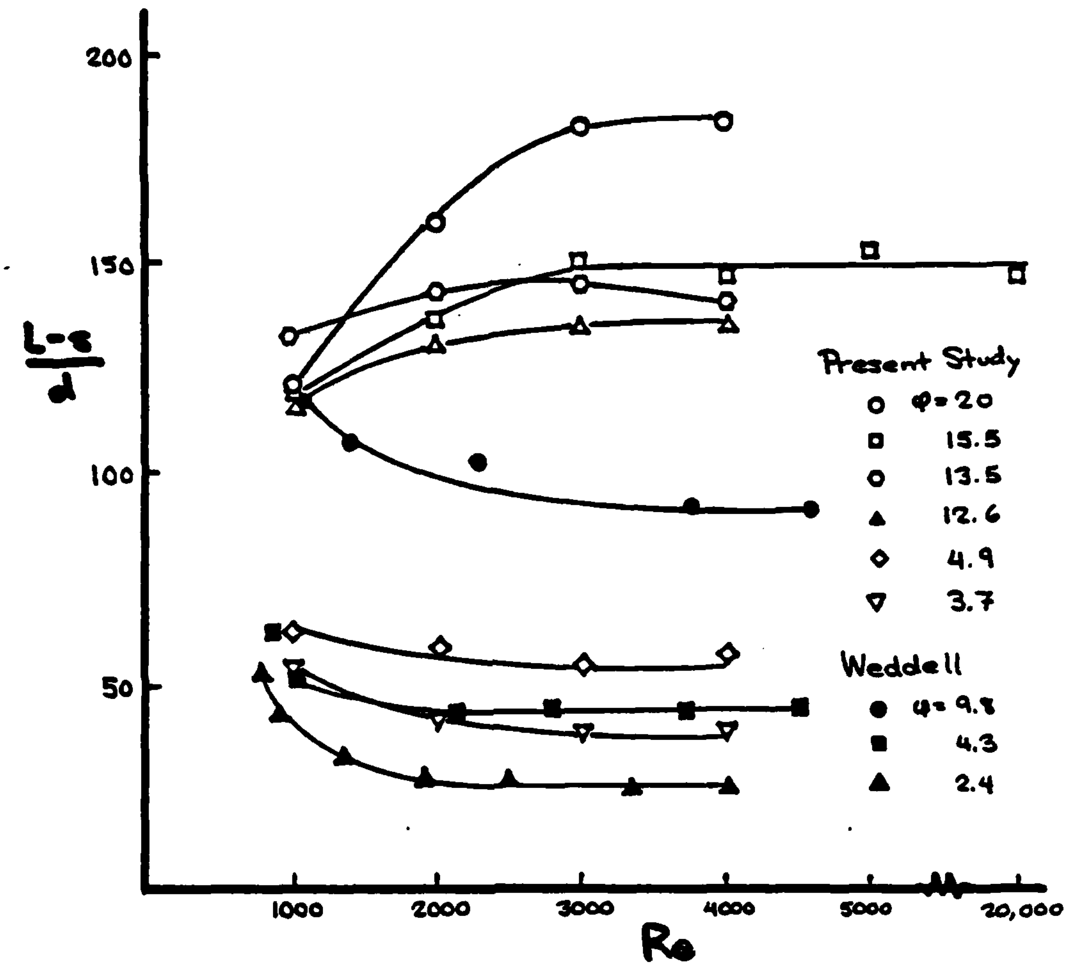


Fig. 8. Flame length versus Reynolds number Re and equivalence ratio ϕ.

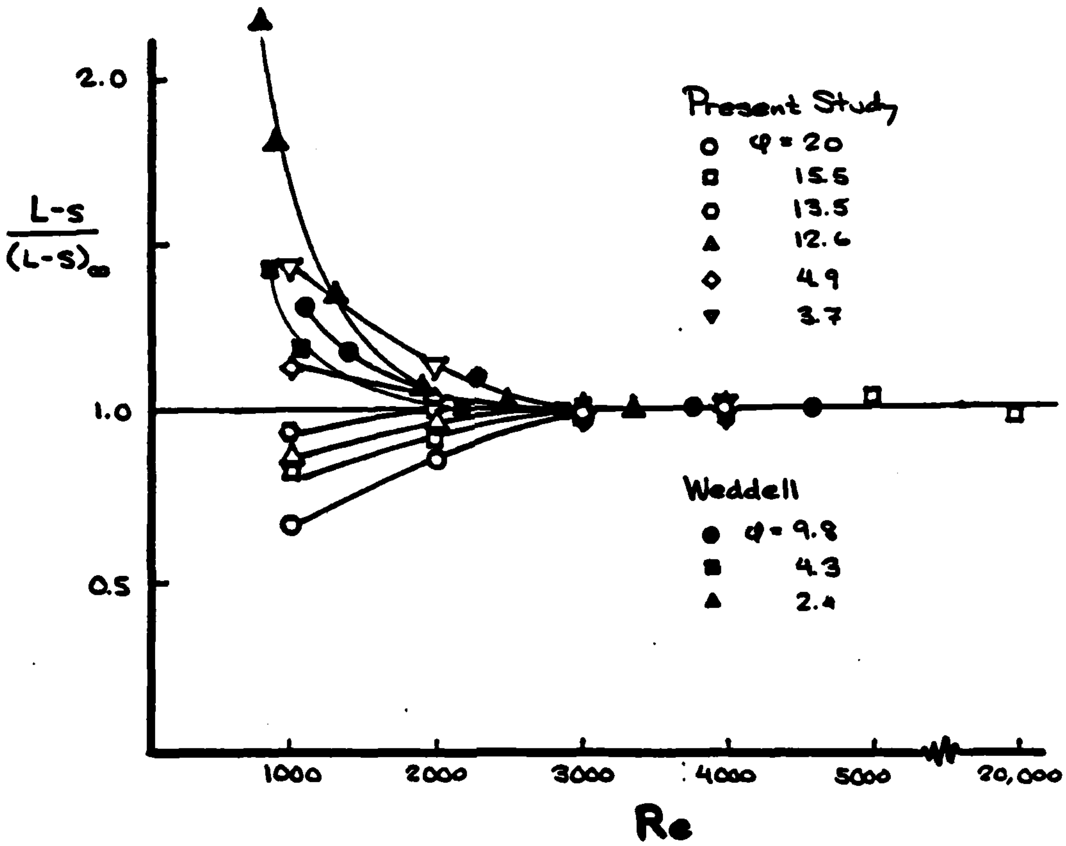


Fig. 9. Normalized flame length versus jet Reynolds number Re and equivalence ratio ϕ.

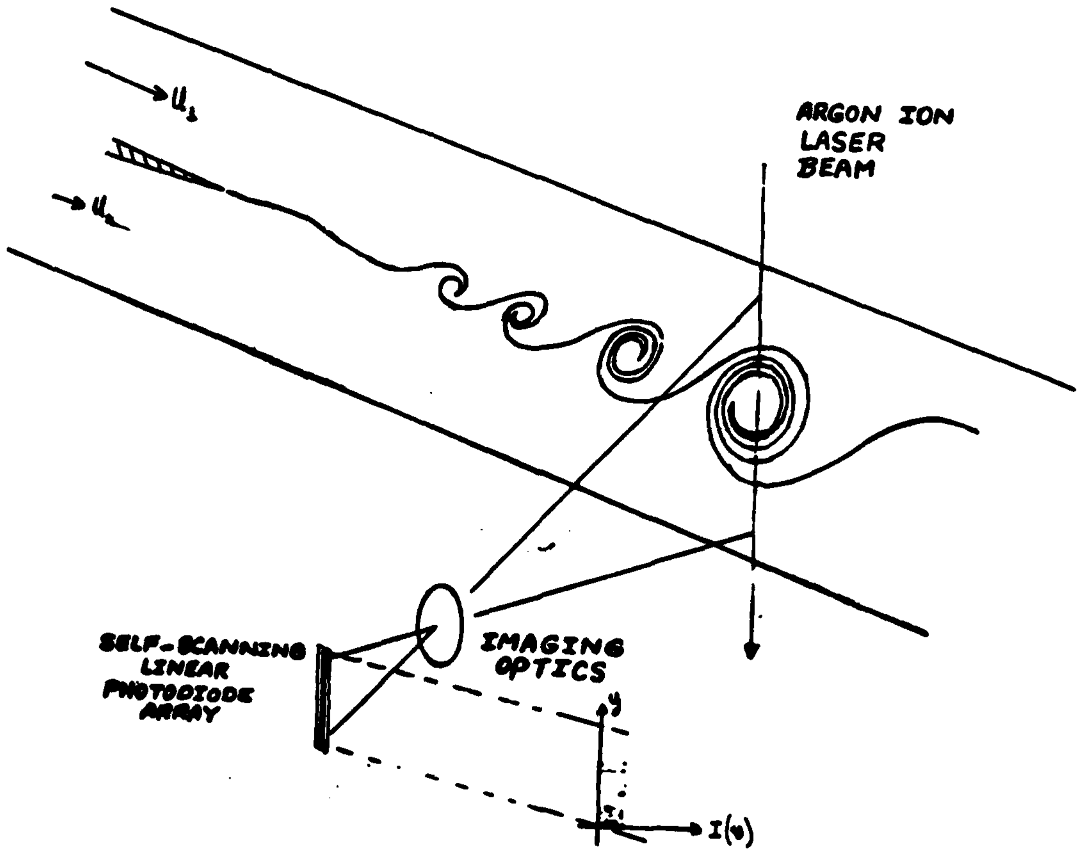


Fig. 10. Schematic optical and image array layout for digital image Laser Induced Fluorescence data acquisition in a non-reacting two-dimensional shear layer.

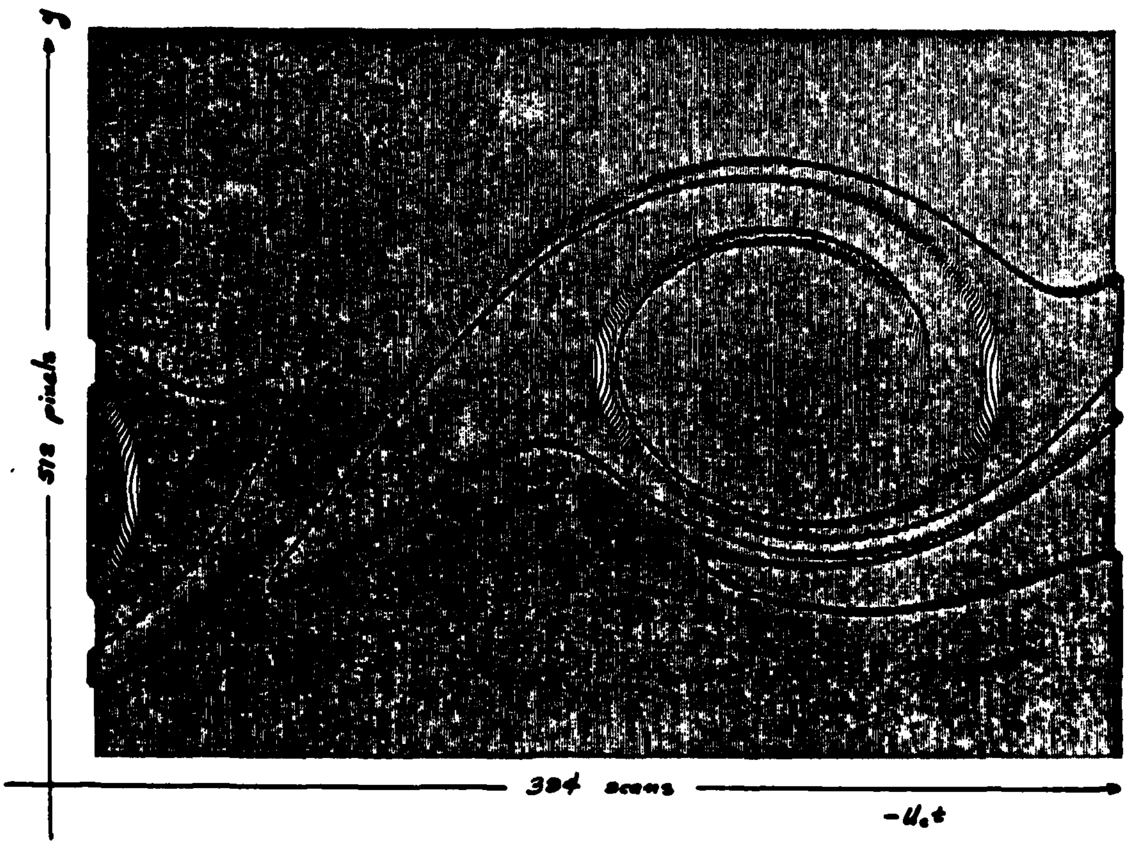
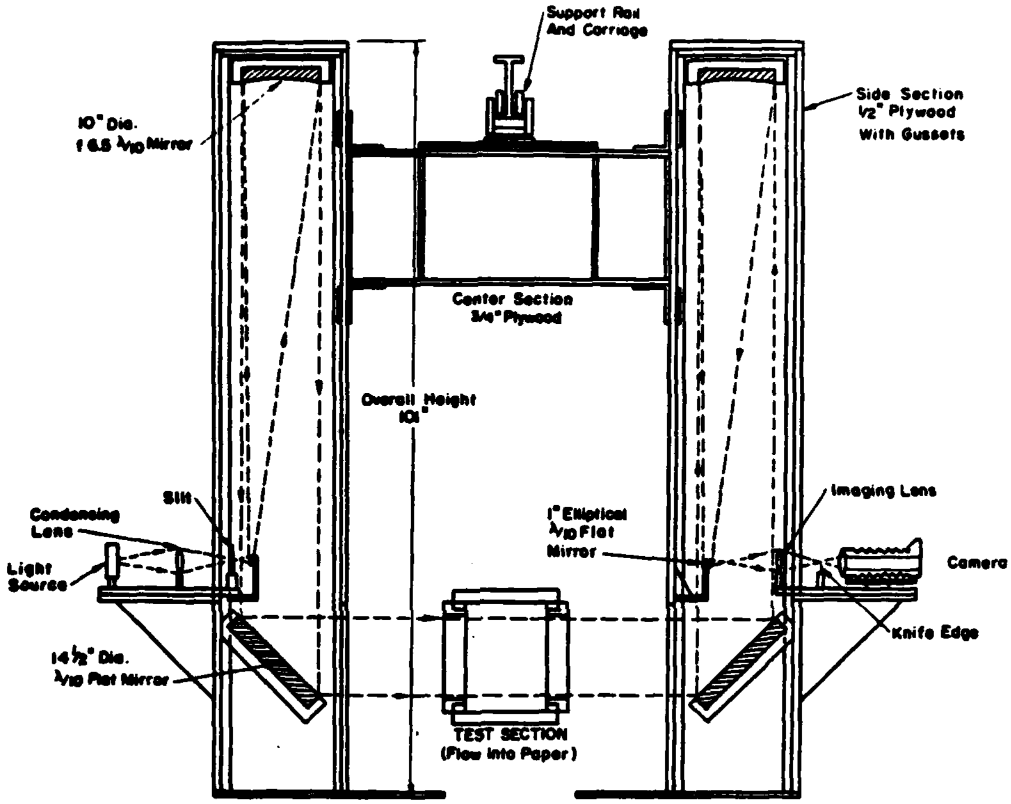


Fig. 11. Sample LIF data in a two-dimensional mixing layer (Re = 1,000). The time axis would have to be stretched by about a factor of 4 to match the streamwise to crosswise length scales. See figure 10.



REACTING SHEAR FLOW LAB SCHLIEREN SYSTEM

Fig 12. Combustion Laboratory schlieren system schematic.

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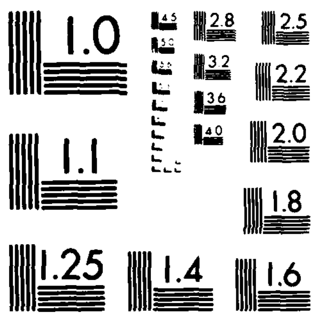

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work under this contract has proceeded along three main lines, (i) an experimental program covering low heat release combustion of hydrogen and fluorine, and chemically reacting turbulent shear layers and jets in water, (ii) a theoretical model development program whose aim is to provide alternatives to gradient diffusion transport models, and (iii) a diagnostics development parallel program to advance the state-of-the-art in experimental techniques, as dictated by our main experimental effort. Substantial

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progress has been made in all three areas. Notably, in the experimental program, we have completed a first set of measurements in our $H_2 + F_2$ combustion facility, as well as laser induced fluorescence measurements of chemically reacting jets and shear layers in water. These experiments prove conclusively that gradient transport models are inappropriate in describing these flows. In the theoretical area, we have shown good agreement between a simple mixing model, developed under this contract sponsorship, and our measurements. In the diagnositcs area, important advances have been made in laser Doppler velocimeter, high speed thermometry, laser induced fluorescence and others.

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